JERS-1 Synthetic Aperture Radar Interferometry Applications: Mapping of Rain Forest Environments and Crustal Deformation Studies

Paul A Rosen, Scott Hensley, Gilles Peltzer, Eric Rignot, Charles Werner
IFSAR Algorithms and System Analysis Group, Jet Propulsion Laboratory, NASA
4800 Oak Grove Drive, Pasadena, CA, 91109, USA
Tel: 818.354.0023, Fax: 818.393.3077, Email: par@parsar.jpl.nasa.gov

Abstract

We proposed to use the methods of synthetic aperture radar interferometry applied to JERS-1 L-Band data to accomplish two objectives: 1) to refine topographic change mapping capabilities at L-band (24 cm wavelength) at areas of active seismic and volcanic deformation 2) to use interferometric techniques to monitor rain forest environments. The first objective follows from several very powerful demonstrations of the ability of L-band radars to map centimeter level deformation along the radar line-of-sight direction over very wide areas. Refinement in understanding the limitations to the technique of signal decorrelation and atmospheric propagation errors have led to the development of more robust observing strategies and complementary data set definition. The second objective is relatively new in application to rain forests. The idea was to measure topography in rain forest where little digital topography is available, and to study a time series of interferometric correlation measurements to monitor deforestation.

This research using JERS-1 SAR data has been very fruitful, resulting in a strong collaboration with geodesists and geophysicists in Japan, and several important papers characterizing crustal deformation, and the capabilities and limitations of JERS data for these studies. An important new area of data utilization that has come out of this research is in damage assessment after an earthquake. Clear evidence in JERS data of interferometric decorrelation in the Kobe city area caused by building failures during the 1995 earthquake indicates that a properly designed SAR system can contribute powerful hazard assessment and mitigation capabilities to civil protection agencies. In the area of rain forest mapping, the multi-temporal measurements of the interferometric correlation was shown to be a valuable input to the identification of deforestation signatures.

1. *Key Results for Rain Forest Mapping*

A number of JERS images of tropical rainforest in the Amazon were ordered to serve two main scientific purposes. One is to determine the feasibility of constructing reliable topographic models in areas for which topography is required for ecological studies. Another is to determine the potential of JERS-1 SAR amplitude and interferometry data at monitoring deforestation and regrowth of tropical forests.

The first site of study is the Manu National Forest Park, in Peru, where we collaborate with Dr. John Tergorh and his group to map tree species along the Rio Manu floodplains. A NASA/JPL campaign was flown in this area in 1993 and brought important new data on this region, but concentrated on the floodplain regions. Hilly terrain could not be analyzed properly because of a lack of an accurate digital elevation model of the area.

Using three JERS-1 scenes from 1995 and 1996 we generated interferometric fringes over Manu National Park. Unfortunately, fringes were only obtained in an area away from the Park and our two attempts at obtaining fringes on the Park itself failed. We therefore hope to access more data collected by JERS-1 in this region in order to find a good interferometric pair.

The second site of study is near Porto Velho, in the state of Rondonia, Brazil. We have studied this site extensively using SIR-C 1994 data, a time series of Landsat/SPOT data, and field work in 1995. The result was a landcover map shown in Figure 1 which combines both optical and radar. During that preliminary study, we examined a couple of JERS-1 scenes but our assessment indicated that those data were not providing a reliable assessment of the fraction of deforested land.

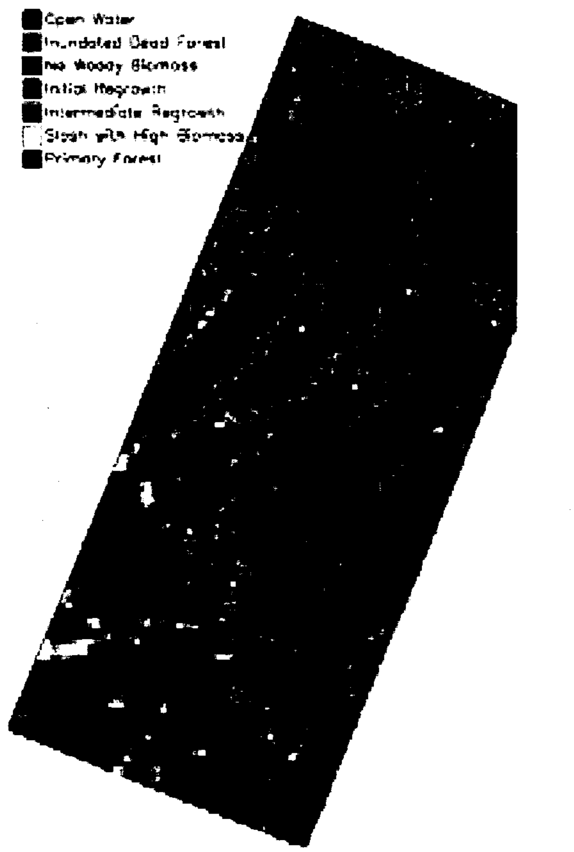

***Figure 1** : Classification of rain forest using Landsat/ SPOT and the SIR-C SAR data*

The new JERS-1 data we received from this region indicate that multi-temporal data and especially interferometry data could greatly benefit this research. Figure 2 shows a black and white, enhanced JERS image of the study site collected in July 1996. Contrary to images collected during the wet season, images collected in the summer provide a very nice contrast between undisturbed forest and deforested areas, as outlined by the comparison with the SIR-C/Landsat classification. A further improvement in separability of undisturbed forest from disturbed forest is given by the addition of interferometric information.

***Figure 2** : JERS Radar Brightness image of rain forest deforestation*

In Figure 3, phase coherence between July and August 1996 is colored red, while the July and August images are respectively colored green and blue. Cleared areas stand out as bright green because phase coherence is high in these areas. Undisturbed forest exhibits lower levels of phase coherence. Hence, this additional information helps better separate cleared versus non-cleared land. We are currently in the process of evaluating the improvement in classification accuracy of these data in order to quantify the results and we plan to publish the results in the open literature in the near future.

The relevant findings of this research are that: 1) constructing topographic models in tropical regions requires the processing of many image pairs; 2) data must be collected in the dry season to guarantee the success of mapping; 3) multi-temporal JERS-1 data and especially interferometry data help better identify disturbed forest areas, and we are now looking at the possibility of characterizing forest regrowth and the dynamics of deforestation using JERS-1 data.

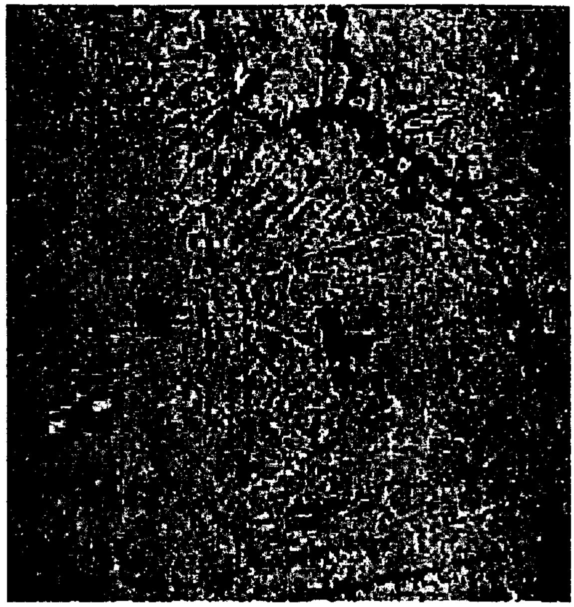

***Figure 3** : Red/Green/Blue overlay of radar brightness and decorrelation in rain forest environment. Red encodes decorrelation, Green and Blue the brightness on two days used to make the interferometric measurement*

2. *Key Results for Topography and Crustal Deformation Studies*

2.1 *Topography*

One of the objectives of this study was to understand the usefulness of JERS interferometric data for generating topographic products. One of the first sites of study is shown in Fig.4, depicting the Unzen Nagasaki area. An interferogram was formed from imagery acquired 44 days apart. The phase of the interferogram was unwrapped, and assuming the coastlines to be at an altitude of 0 m, an accurate interferometric baseline was estimated. From these data, it was possible to construct a geocoded digital elevation model shown in the figure in perspective view. This map has a statistical accuracy of about 40 m, but because of phase unwrapping errors, and tropospheric and atmospheric artifacts, we expect the absolute error to be larger, at about 100 m in many places.

The conditions for generating a topographic product in this case were quite favorable: the baseline was around 500 m, so the phase had good sensitivity to topography, but not too much to prevent phase unwrapping. The correlation was good because the data were acquired in winter over the minimum JERS cycle of 44 days when the vegetation was not appreciably in motion.

In general for JERS, the conditions for topographic mapping have not been as favorable. Usually, the interferometric baselines are either too large or too small, or the repeat cycle is too large for good correlation. The ability to unwrap the phase is often the limiting factor in generating topographic maps, and for JERS, even if enough data were available to average noisy JERS-derived interferograms to compute a finer accuracy product, it would be difficult to do so because unwrapping is necessary.

***Figure 4** : Perspective topographic image of Unzen and Nagasaki area generated from a JERS interferogram. Despite steep slopes and considerable vegetation, a credible digital elevation model can be constructed. The vertical accuracy at 100 m resolution is roughly 40 m.*

Several strategies have been developed over the years to use an auxiliary, known, DEM to remove most of the fringes before unwrapping, but we have not pursued these methods here because there is either no need over our sites of interest because topographic data of sufficient accuracy exists already for use in science investigations, and because data are often simply not available in sufficient quantity outside of Japan.

The importance of this work is to show that given data of the appropriate characteristics, topographic products can be generated. Given enough data of this quality, accuracy can be improved through averaging. Clearly however, repeat pass interferometry should not be used for generating topography unless there is no other source of accurate topographic information. There are simply too many sources of error to mitigate.

2.2 Crustal Deformation

While JERS data, and repeat pass data in general, are not suitable for generating accurate topography, crustal deformation studies have been revolutionized by the precise images of geodetic change made possible by repeat pass interferometry. Figure 5 shows a stunning example of the power of interferometry to image an earthquake using JERS data, in this case the Northridge earthquake of 1994.

This interferogram was generated with the use of a 10 m resolution, 1 m vertical accuracy digital elevation model created from the NASA/JPL TOPSAR airborne interferometric mapper. Despite a too large baseline producing fast fringe variations, by processing the data at full resolution, and using a fine accuracy DEM as reference and to remove topography from the interferogram, this product was generated.

Note that there are several areas in Fig. 5 near the region of maximum uplift are decorrelated. In order to render the data most scientifically useful, we have invested a considerable amount of effort into methods to unwrap extremely noisy data, in particular data so noisy that there are isolated regions of correlated data surrounded by a sea of pure noise. The Northridge interferogram in Fig.5 is not so bad, but has quite a bit of noise. Much of the decorrelation is attributed to massive landslides in the Santa Suzanna mountains where the region of maximum uplift is centered.

***Figure 5** : Deformation due to the Northridge 1994 earthquake as depicted in a JERS-1 interferogram. Large concentric fringes in upper left are the signature of the earthquake*

Figure 6 shows the result of unwrapping the noisy interferogram in Fig. 5. Note Fig. 5 is in natural radar coordinates while Fig. 6 is geocoded in a UTM projection. The unwrapping method was developed by Mario Costantini to solve problems in topographic mapping, where the desirable input data are as highly correlated as possible. We have studied the unwrapping properties in the noisy environment of long time separation interferometry. The results in Fig. 6 are quite striking, showing the complete deformation field of the Northridge earthquake with unprecedented fidelity and completeness. We are currently extending these algorithms to deal with truly sparse, disconnected phase regions, expecting to use model assumptions about the deformation to help tie together the disconnected regions.

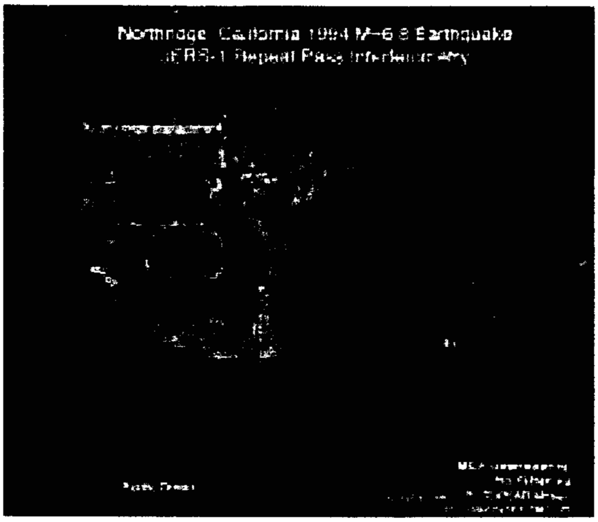

***Figure 6** : Geocoded displacement field of the Northridge earthquake derived from fully unwrapped interferogram*

Kobe was an area where considerable progress was made in understanding the potential benefits of interferometric monitoring. Figure 7 shows an interferogram of the Kobe earthquake. This was the first high quality interferogram produced of this area. Publication was withheld in deference to my Japanese colleagues. Together, we conducted field surveys of the damaged areas looking for indications of phase discontinuities and loss of coherence. The montage of photographs in Fig. 7 associated with the correlation map (blue/purple/yellow = low/medium/high correlation) illustrates the relationship between surface conditions and interferometric change. On Awaji, the correlation is low in general because the area is mountainous and vegetated. One area near the main break on the northwest side of the island is being stripped for landfill, so naturally the image decorrelates completely there. The area of the main break itself decorrelates due to considerable ground motion.

The Kobe coast is nearly uniformly urbanized, so one would expect that the correlation would be uniformly high everywhere if there were no destruction because buildings do not change much in general over time. Away from the band of buildings on the coast, there is mountainous vegetated terrain, so the correlation is naturally low.

The resulting destruction in the urban areas from the earthquake was not uniform as can be seen from the correlation map. In fact, destruction was worse away from the extension of the main break in Kobe that it was in Kobe itself. After field work, it became clear that there was much more massive building collapse toward the east than in the central region and westward. This is because much of the eastern area is built up on landfill with no firm anchor to bedrock. Buildings in this are failed, whereas in more stable area, destruction was primarily due to fire, which tended to be localized. Figure 7 shows several examples of building collapse at a port area, and wholesale subsidence of an island by nearly 1 meter relative to an elevated freeway anchored to the bedrock. This shows that the interferometric correlation

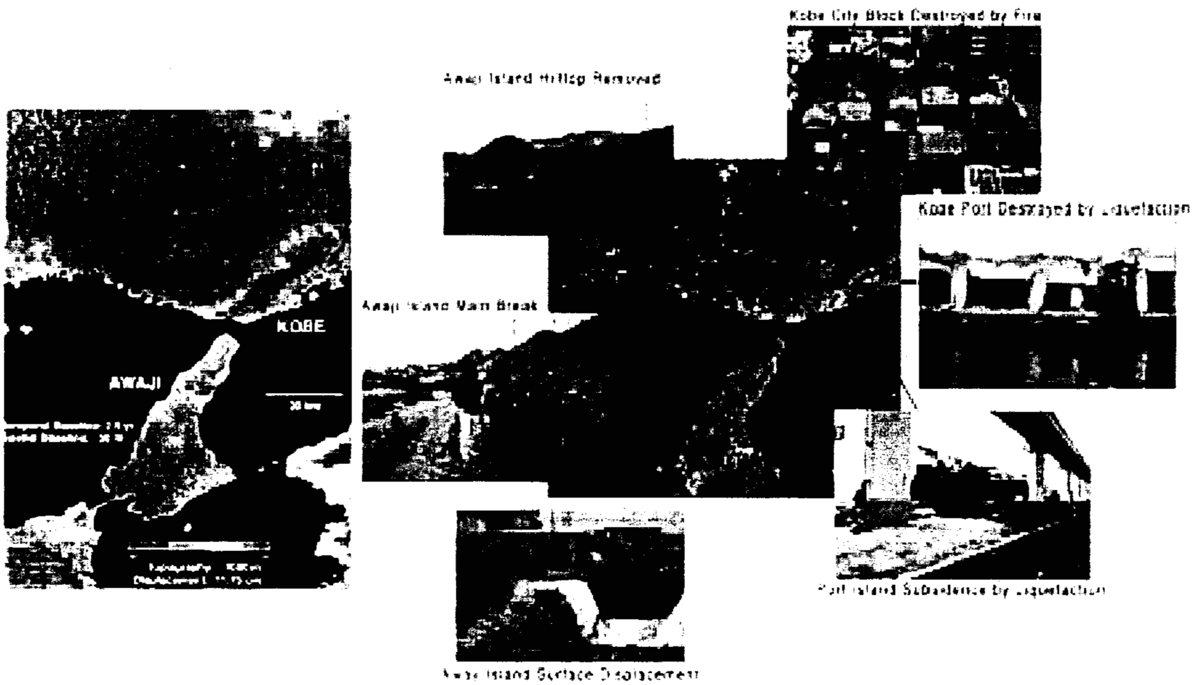

***Figure 7** : Interferogram (left) and correlation montage (right) of the Kobe area formed from images surrounding the 1995 Kobe earthquake. Fringes maintain coherence in all areas despite a 2.5 year temporal baseline, except where surface disruption due to ground motion occurred.*

is a sensitive discriminant of damage and potentially may be used as a tool to assess damage.

From one interferogram or correlation map, one cannot distinguish the earthquake destruction and vegetation or baseline signatures. The key to developing an operational system for damage assessment is frequent repeated observations of a site that allow a full characterization of the temporal variability of the city relative to the surrounding areas. Future satellites will likely produce such data sets.

2.3 *Longevity Studies*

We were very encouraged by the results above, and decided to push the limits of the technique as far as possible. Aided by Sean Buckley, a graduate student at University of Texas, Austin, we attempted to look at very long temporal separations of images in areas that traditionally give great difficulties to interferometry: vegetated agricultural areas.

Figures 8-11 show areas in Vietnam and China that are farmed. In all cases, there is patchy correlation, with faint fringes visible because the pattern of correlated areas is dense enough to allow the eye to follow the slow variations of the phase.

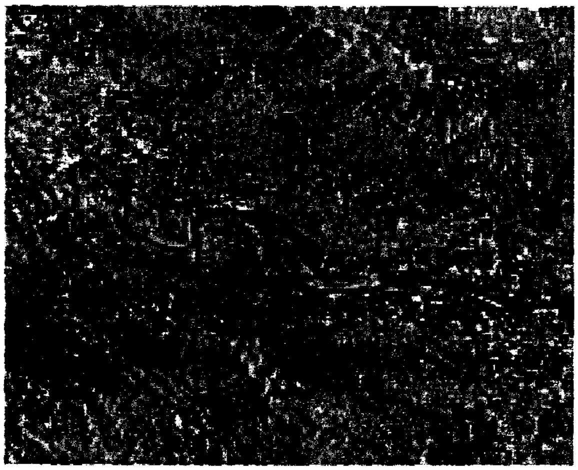

Figure 8 *: 3-year interferogram of a region west of Hanoi, Vietnam. The region is largely vegetated*

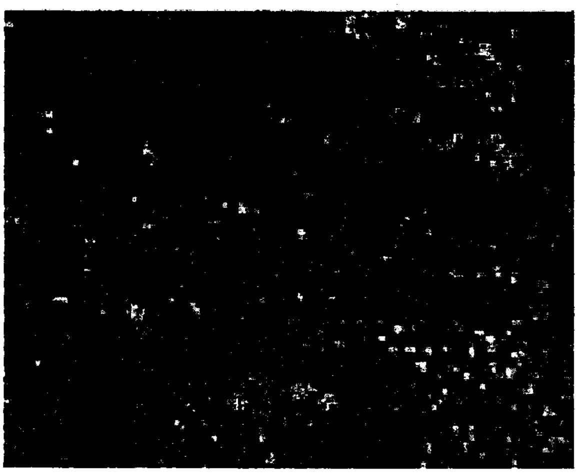

Figure 9 *: Correlation map of a region west of Hanoi, Vietnam depicted in Figure 8*

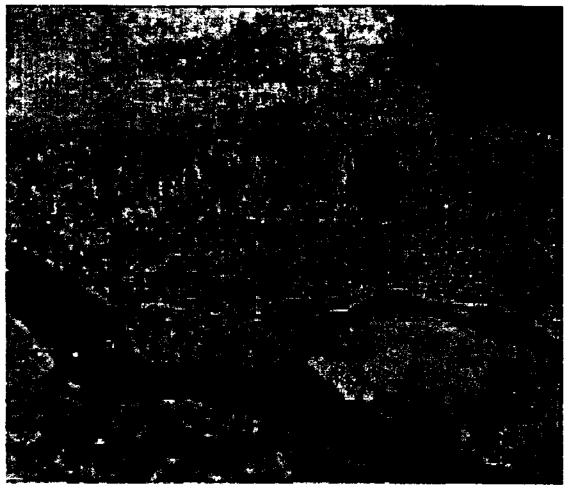

Figure 10 *: A 4-year interferogram of Nantong, China, an agricultural rural area, showing good quality fringes over much of the area, as in Figure X*

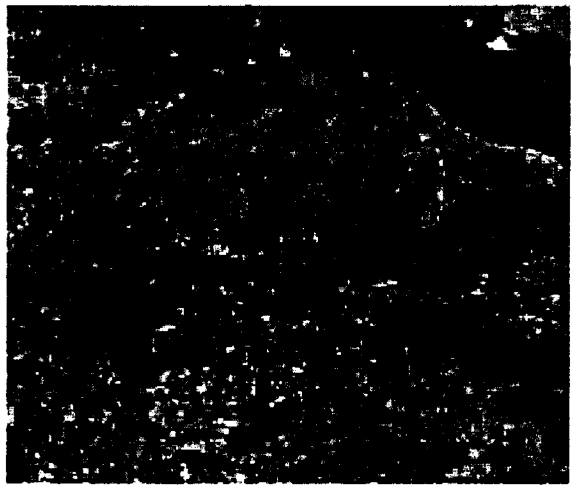

Figure 11 *: Interferogram of Yangcheng-Hu, China, an agricultural rural area. The interferogram is formed from images acquired 5 years apart, but there are still fringes in the town and roads, suitable for studying large scale deformation of the area*

These results show that correlation is preserved in difficult environments over very large time periods, beyond 5 years. The key to making use of these data for crustal deformation studies is to find a way to connect the isolated areas of good quality phase. As mentioned previously, this is an active area of research.

The explanation of the existence of correlation is as follows. Fields and forests clearly decorrelate over time, but towns and paved roadways, as well as cultural features on the roadside, stay largely correlated over time. So these interferograms have patches of correlation in the towns, often accompanied by linear correlation features caused by roads or roadside features. In the sparse phase unwrapping methods, these properties can be exploited to improve unwrapping performance.

2.4 *Other sites studied*

Several other sites were studied but are not reported here. Colleagues who are also investigators in the NASDA research initiative will present their results in this forum, and the results have been published (see list below). The sites include:

1. Izu Peninsula - a detailed and extensive study was carried out in collaboration with S. Fujiwara and M. Tobita at GSI of the baseline and temporal decorrelation properties of the JERS data over the Izu peninsula in Japan, including field studies of the terrain characteristics. Over 45 interferograms were formed and examined for deformation and correlation signatures. We concluded that baseline decorrelation appears to become non-linearly worse as the baseline increases, emphasizing the need for small baselines in crustal deformation measurements. We also concluded that there was very little temporal decorrelation in the data, most of it being baseline related or volumetric in the vegetation. A comprehensive paper was published in JGR.
2. Sakhalin earthquake - We studied the coseismic and post-seismic signal of the recent large Sakhalin earthquake. The correlation in the scene was preserved despite a freeze-thaw difference in the images forming the interferogram. A paper on the coseismic signal was published in Earth Space and Planets.
3. Kagoshima Earthquake - We studied the coseismic signal of the Kagoshima earthquake and compared it to GPS measurements. The data were not entirely reconcilable, indicating that there may be complications to the assumed simple fault parameters inferred from modeling. A paper was published in GRL.
4. Sumatran earthquake - Data was ordered covering a large earthquake in Sumatra. Unfortunately, despite much processing of data, the baselines and time separations were not favorable, so no crustal deformation measurements could be inferred.

3. *Future Outlook*

Interferometry is a rapidly expanding field of remote sensing. JERS, by virtue of its repeated imaging of several areas often, has generated numerous examples of the power of L-band interferometry for crustal deformation studies and nascent vegetation studies. While JERS is no longer operating, several L-band sensors are likely to be orbiting in the near future. Work must be done to educate science planners to the needs for frequent repeated measurements of a site of interest in order to mitigate the usual limitations of repeat pass interferometry: decorrelation and propagation artifacts.

Another area of increasing importance is understanding the relationship of the dense GPS network of tropospheric and ionsopheric delay measurements in Japan and the SAR interferometric measurements. There is sufficient JERS acquired up until 1998 to address some of these issues. Preliminary results with H. Nakagawa of GSI show intriguing though faint correspondence of GPS delays with SAR delays over Tokyo city surrounding Tokyo bay. When these large spatial scale signals in the SAR can be understood, and potentially calibrated using GPS, a more subtle interferometry over much wider areas and observing smaller deformation signatures will be possible

4. *Aknowledgements*

This research was made possible by support from the NASA Topography and Surface Change program, Earnest Paylor Manager, and by generous supply of JERS raw signal data through the NASDA Global Rainforest Mapping and Inteferometry Research Initiative. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

5. *References*

[1] S. Fujiwara, P. A. Rosen, M. Tobita, M. Murakami; "Crustal deformation measurements using repeat-pass JERS-1 Synthetic Aperture Radar interferometry near the Izu peninsula, Japan", Journal of Geophysical Research, 103(B2) 2411-2426, 1998

[2] M. Tobita, S. Fujiwara, S. Ozawa, P. A. Rosen, E.J. Fielding, C. L. Werner, M. Murakami, H. Nakagawa, K. Nitta, M. Murakami; "Deformation of the 1995 North Sakhalin earthquake detected by JERS-1/SAR interferometry", Earth Planets Space, 50, 313-325, 1998

[3] S. Fujiwara, H. Yarai, S. Ozawa, M. Tobita, M. Murakami, H. Nakagawa, K. Nitta, P. A. Rosen, C. L. Werner; "Surface displacement of the March 26, 1997, Kagoshima-ken-hokuseibuearthquake in Japan from synthetic aperture radar interferometry", Geophysical Research Letters, 25(24), 4541-4544, 1998

[4] P. A. Rosen, S. Hensley, F. Li, I. Joughin, S. Madsen, E. Rodriquez, R. M. Goldstein, "Synthetic aperture radar interferometry", Proceedings of the IEEE, invited publication 1999